Real-Time Imaging of the Ionosphere over the United Kingdom – Preliminary Results

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ABSTRACT

A novel ionospheric imaging technique has recently been developed at the University of Bath. Known as Multi-Instrument Data Analysis System (MIDAS), this technique is a tomographic algorithm that inverts dual-frequency carrier-phase measurements of Total Electron Content (TEC) to produce maps of ionospheric electron concentration in space and time. Using freely available GPS observation data from a large number of fixed dual-frequency GPS receivers, the MIDAS method has been very successful in mapping the horizontal distribution of vertical Total Electron Content (TEC) over the European region. There is, however, a latency of at least 24 hours in the availability of the GPS observation data. Furthermore, the density of receivers located on the mainland United Kingdom is very small. This makes it difficult to produce maps that show small-scale variations in vertical TEC over the UK.

In this paper, we describe a project to produce detailed maps of vertical TEC in near real time over the mainland UK. Through a collaboration with BAE SYSTEMS, the UK Meteorological Office and the Ordnance Survey, a network of fixed GPS receivers will be used to facilitate the mapping of small-scale variations in vertical TEC. The GPS observation data from this network will be streamed directly to the University of Bath, where it will be processed using the MIDAS algorithm. It is intended that spatially detailed images of the ionosphere over the UK will be then available within one hour, using a purpose designed user interface.

1.0   INTRODUCTION

A novel four-dimensional ionospheric imaging technique was developed at the University of Bath [1], known as Multi-Instrument Data Analysis System (MIDAS). MIDAS inverts dual-frequency relative carrier-phase measurements of slant TEC to find the underlying electron density field. The MIDAS algorithm is a linear least-squares parameter fitting algorithm, which extends the work of Fremouw, et al [2] into three spatial dimensions and one temporal dimension. It has been extensively tested, in both simulated and experimental situations, by [3], [4] and [5].

Currently, the MIDAS algorithm uses archived GPS data that are freely available from the International GPS Service (IGS) and other organisations that are involved with geodetic activities. This leads to a latency of about 24 hours in the production of images. The objective of this project is to develop a system, to be known as MIDAS-UK, that will generate ionospheric images in near real-time.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **01 JUN 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**	
4. TITLE AND SUBTITLE **Real-Time Imaging of the Ionosphere over the United Kingdom Preliminary Results**		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Electronic and Electrical Engineering University of Bath Claverton Down Bath BA2 7AY UNITED KINGDOM**		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**			
13. SUPPLEMENTARY NOTES **See also ADM002065., The original document contains color images.**			
14. ABSTRACT			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **UU**	18. NUMBER OF PAGES **30**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

Ionospheric imaging has been extensively used by the international scientific community to reach a deeper understanding of the processes within the ionosphere and the coupling mechanisms between the ionosphere and magnetosphere. It is envisaged that this will continue well into the future. The main non-scientific use of ionospheric data is currently military, where it is used for propagation prediction for HF communications. There is, however, an increasing commercial interest in ionospheric information, driven by the expanding navigation and aviation business markets. It is believed that the work of this project would contribute significantly to the growing knowledge bases of the scientific, military and commercial areas.

The objective of this project is to adapt MIDAS to be used for real-time ionospheric mapping. New and existing instrumentation will be networked to provide a stream of GPS observation data, which will be inverted to produce images of the ionosphere in near real-time. The images will be made available through a web-based user interface, and an archive of observation data will be built up.

2.0   PROPOSED METHOD

In this section, the proposed method for generating the ionospheric images will be presented. The data sources and arrangements for obtaining these data will be described first. The main requirement, as far as this project is concerned, is the timely arrival of receiver observation and satellite orbital data in sufficient quantities to ensure a useful image. The problems with using existing data sources is that the data is at least 24 hours old when it becomes available, and there is very sparse data covering the mainland UK. The arrangements for obtaining the data that the project requires will be described. We will then describe our proposed methodology for generating the ionospheric images in real time, and how the resulting images are to be verified and distributed.

Current practice is to obtain the receiver observation and satellite orbital data by FTP from the Scripps Orbit and Permanent Array Center (SOPAC – sopac.uscd.edu) at the University of San Diego. The observation data are in Receiver Independent Exchange (RINEX) format that has been compressed. RINEX files are text files that list, in text form, the L1 and L2 carrier phase and pseudocode path lengths to each satellite in view, sampled every 30 seconds. The orbital files give the positions of all the GPS satellites every 15 minutes, with a latency of about 17 hours . The latency of the observation files is about 24 hours, although a small number of files are available in near real time.

A problem with the existing data source (SOPAC) is that there are only two receivers in the UK that contribute data to the archive. However, the Ordnance Survey (OS - the UK's national mapping agency) and the UK Meteorological Office both maintain private networks of GPS receivers. Both of these organisations deposit their GPS observation data with the British Isles Gps archive Facility (BIGF) archive (www.bigf.ac.uk), making about 80 receivers available over the UK mainland. This is more than sufficient to produce a stable image. However, there remains the problem of data latency. Data will be obtained from the BIGF archive when necessary.

The timeliness of the data has been addressed by a private arrangement with the Ordnance Survey, in which we have been granted access to the data files on an hour-by-hour basis, as they become available. Additional data from the IGS network will also be used to supplement the reconstructions as required. OS has kindly agreed to supply hourly RINEX observation files for the fixed GPS receivers operated by them. Ultra-Rapid satellite orbital data will be obtained by FTP from the SOPAC archive.

The method is shown diagrammatically in Figure 1, and can be summarised as follows. Hourly GPS observation data from the OS receivers is filed by the OS in compressed RINEX format. At the end of the hour, and after a short delay to ensure that the data files have been deposited in the FTP directory, the data are collected by an automatic FTP script. They are then un-compressed, filed, and structured ready for the

MIDAS inversion. Satellite orbital data is also collected as it becomes available. The inversion will then be carried out. The inversion is based on a three dimensional grid of voxels, each of which has constant electron density and is bounded in latitude, longitude and height. A linear time dependence is introduced for the change in electron density [1]. From past experience, it is expected that the inversion will take about 5 minutes to complete.

At the completion of the inversion, any images generated from it will be about 30 minutes old. A forecasting algorithm, developed by [6], will then be used to recover the 'lost' time and hence to estimate the current state of the ionosphere. Thus, referring to Figure 1, the observation data for the first hour is collected by FTP at the start of the second hour then inverted. The prediction algorithm will then be used to update the images to reflect the current state of the ionosphere.
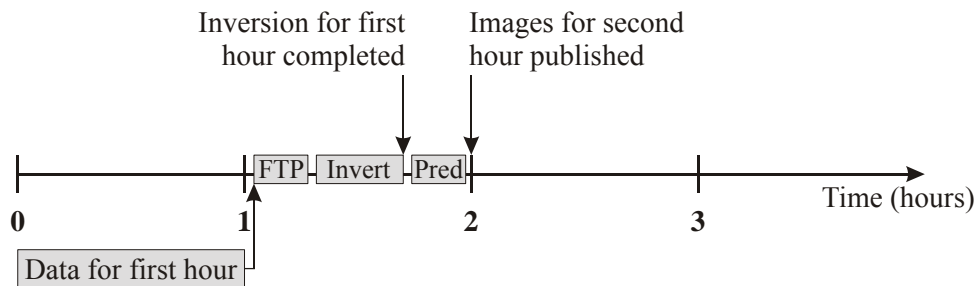
Figure 1: Diagrammatic representation of the process

A review of different types of ionospheric modelling and forecasting is given in [7]. The prediction method of this project makes use of the International Reference Ionosphere (IRI) [8, 9], which is an empirical model used by many in the ionosphere community. A number of methods have been tested for both local and wide area TEC forecasting [6]. In the simplest approach, the most recent TEC measurement is used as a forecast over a short timescale. Clearly, this becomes less valid as the forecast time increases. A less crude approach would be to use the TEC measurement from the previous day at the forecast time. This method will not forecast large day-to-day variations such as would occur during periods of high geomagnetic activity. Other methods involve using the average TEC temporal gradient over the preceding few days, or using a matching algorithm to search historical TEC data to find similar conditions.

The approach under consideration here makes use of the IRI model [8, 9]. IRI gives a good estimate of the monthly median TEC, but cannot be expected to forecast short-term (i.e., day-to-day) variability. However, the changes in IRI-computed TEC have been used to forecast changes in measured TEC using the following procedure [6]:

- Create separate MIDAS and IRI TEC images for Europe

- Calculate IRI percentage changes at each location for the forecast period

- Apply these gradients to the MIDAS image to produce a forecast

This method can be expressed as:

$$TEC_{t+\tau} = TEC_t * \left[1 + \frac{TEC_{t+\tau}^{IRI} - TEC_t^{IRI}}{TEC_t^{IRI}} \right] \qquad [1]$$

for forecast period, τ, and current time, t. An example of this approach is shown in Figure2. Figure 2a shows a vertical TEC map generated by MIDAS for 13:00 UT on day 101, 2002, using post-processed data. The corresponding IRI TEC map is shown in Figure 2b. In Figure 2c, the TEC map for 13:00 UT

predicted from the measured TEC of 12:00 UT, and in Figure 2d is the TEC map predicted from the measured TEC of 10:00 UT. It can be seen that there is good qualitative agreement between the predicted TEC maps and the original one.
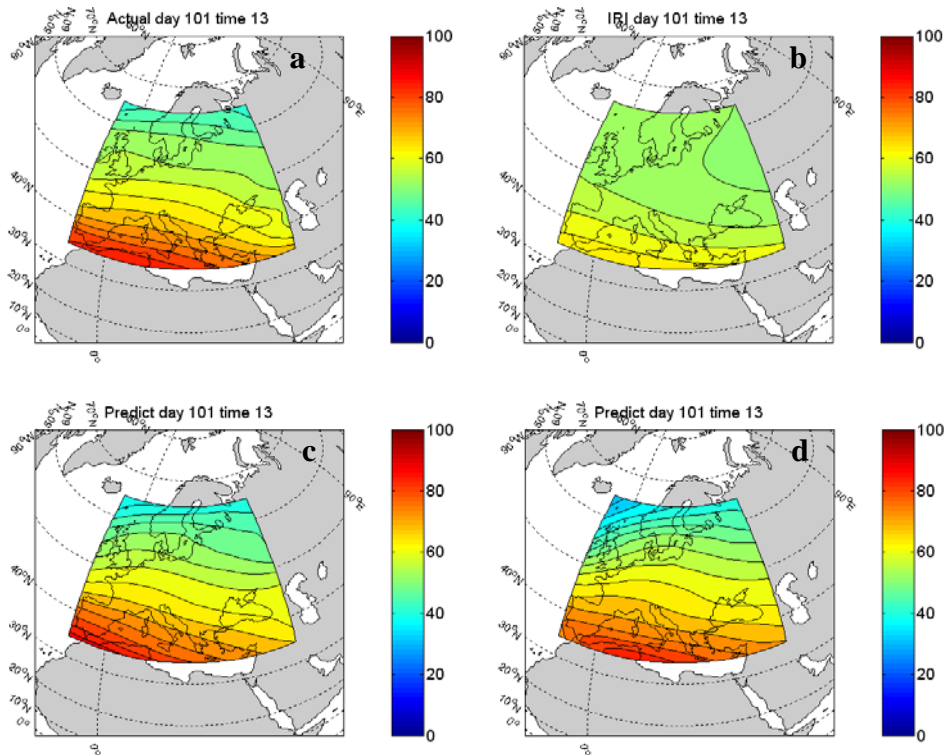

**Figure 2. Vertical TEC images for 13UT, 25th April 2002, in TEC units. MIDAS (a),
IRI model (b) and IRI gradient forecasts for 1 (c) and 3-hour (d)**

The images will be validated by comparison with data from UK-based ionosondes. Data from the ionosonde at Chilton is freely available from the World Data Centre at www.wdc.rl.ac.uk. BAE SYSTEMS also operates an ionosonde, located at Great Baddow, UK. Data from this instrument will be obtained by arrangement. Images will also be compared, both qualitatively and quantatively, with images generated by MIDAS using post-processed data.

3.0   CONCLUSION

A project to produce detailed maps of vertical TEC in near real time over the mainland UK has been described. The project uses a novel ionospheric imaging technique that has recently been developed at the University of Bath. The technique, known as MIDAS, inverts dual-frequency carrier-phase measurements of slant TEC to discover the underlying electron density field. The project will use GPS observation data with a latency of one hour, obtained by private arrangements from the Ordnance Survey of Great Britain, the UK Meteorological Office, and the British Isles GPS Facility (BIGF) archive. It is believed that real-time ionospheric data will be of considerable benefit in planning military HF communication links and will enable civil users of GPS in safety-critical situations to ascertain the accuracy and integrity of the navigation solution. Further results will be reported in due course.

4.0   ACKNOWLEDGMENTS

5.0   REFERENCES

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[3]   Meggs, R. W., C. N. Mitchell, and P. S. J. Spencer (2004), "A comparison of techniques for mapping total electron content over Europe using GPS signals", Radio Sci., 39, RS1S10, doi:10.1029/2002RS002846.

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Real-time imaging of the ionosphere over the United Kingdom

Robert Meggs, Cathryn Mitchell, Robert Watson & Richard Dear

IST-056 Specialists Meeting on "Characterising the Ionosphere"

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Outline

►Issues for real-time ionospheric imaging

  ►What do we mean by real-time?

  ►Latency

  ►Temporal resolution

►Wide-area forecasting of TEC

  ►Problems, methods and solutions

►System architecture

►Computational and data transmission issues

►Summary

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Issues for real-time imaging

►Image *latency* and *temporal resolution*

  ►It takes time to get GPS data and time to invert

  ►Inversion stability is a function of the length of "data window"

►We can overcome these issues by *forecasting*

  ►Standard Kalman filter – co-variance matrices not sufficiently well defined to make a significant impact

  ►"Tricks" will be needed in any approach e.g., persistence, matching model gradients (e.g., IRI)

  ►Feature recognition and motion estimation

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Dealing with latency

ionospheric forecasting

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Forecasting

►We will always have to live with latency

►Single site forecasting :

    ►Cannot be directly applied to wide areas – spatial discontinuities

    ►Does not account for spatial correlation function

►Problem: need to forecast TEC over wide area

    ►Ionospheric structures can move

    ►Spatio-temporal evolution of features

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The real-time system

architecture

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Initial system concept

►Data feeds from GNSS receiver sites

►Centralised image reconstruction

►Centralised image forecasting

►High-level users – *"raw" electron density or TEC*

►Low-level user – *e.g., navigation corrections*

►Transmission of compressed data

►Decompression of correction data

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Data sources
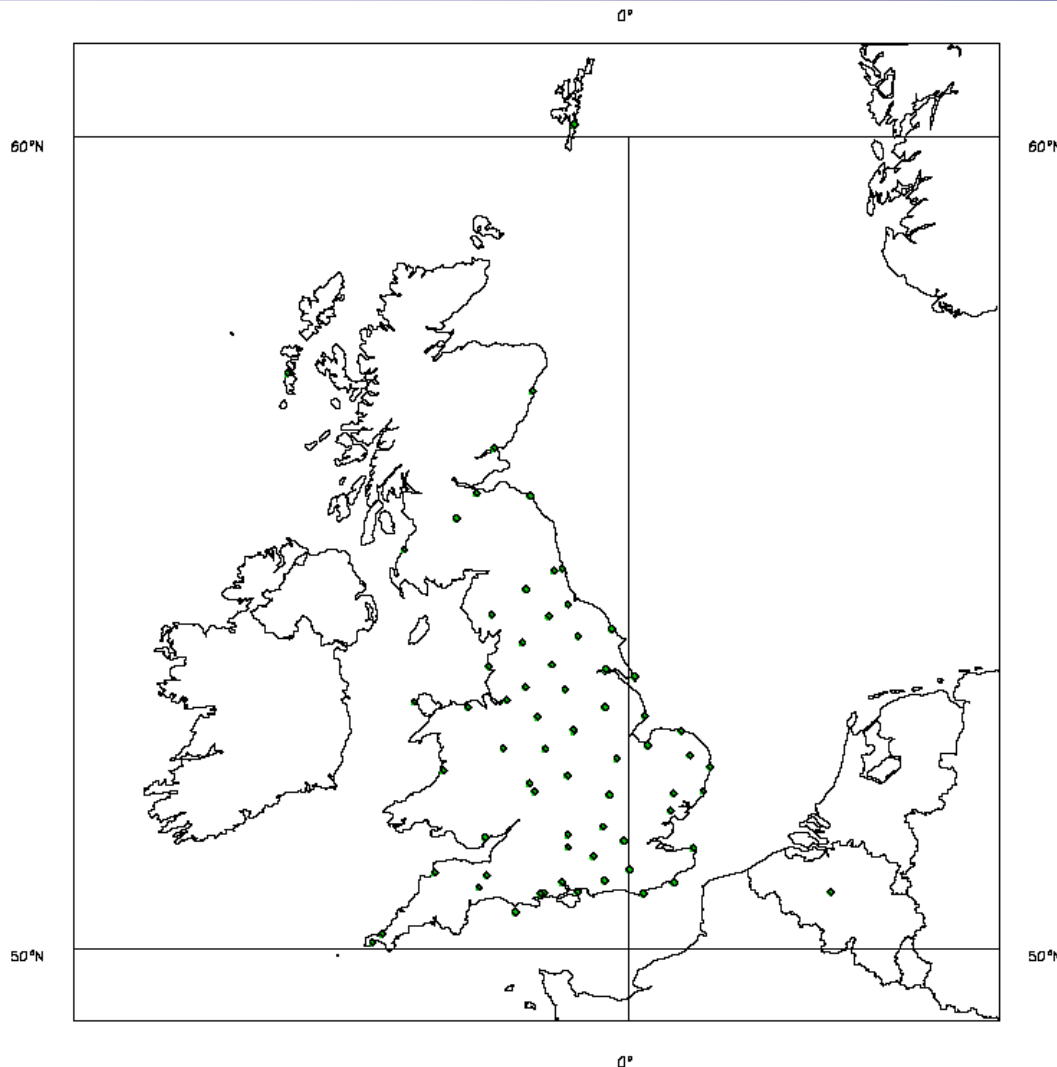
► **Combined network of the Ordnance Survey and UK Met Office**

► **73 receivers provide data in near real-time**

► **Other data:**
  ► **BAE SYSTEMS ionosonde (R-T)**
  ► **PPARC Chilton ionosonde (Not R-T)**

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Data processing timeline
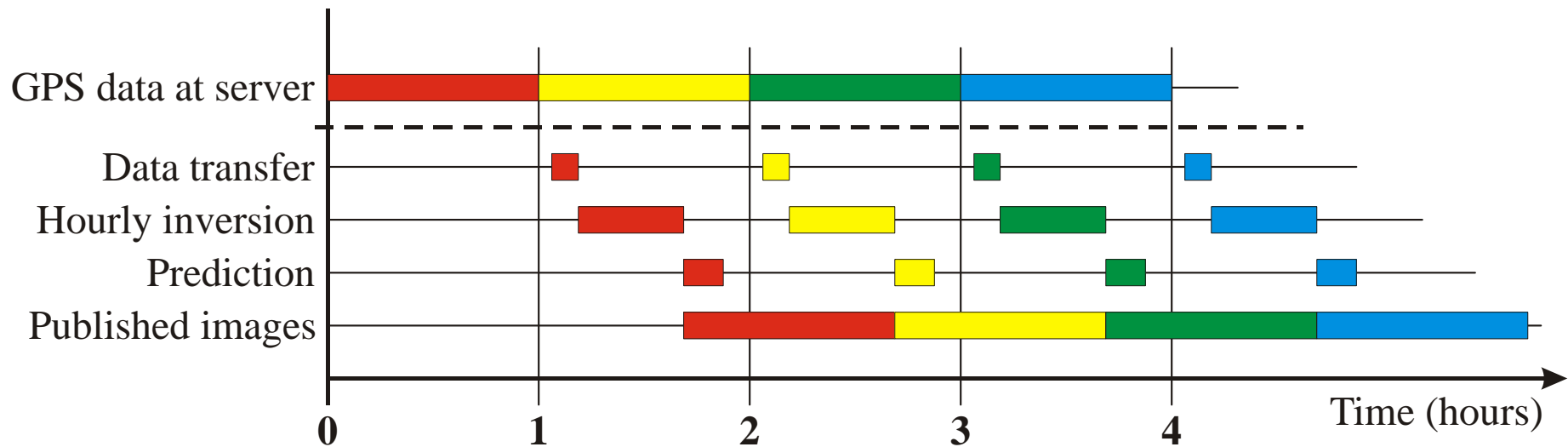
At least two possibilities depending on the user

►Discrete: e.g., 1h windows, generating 1h images
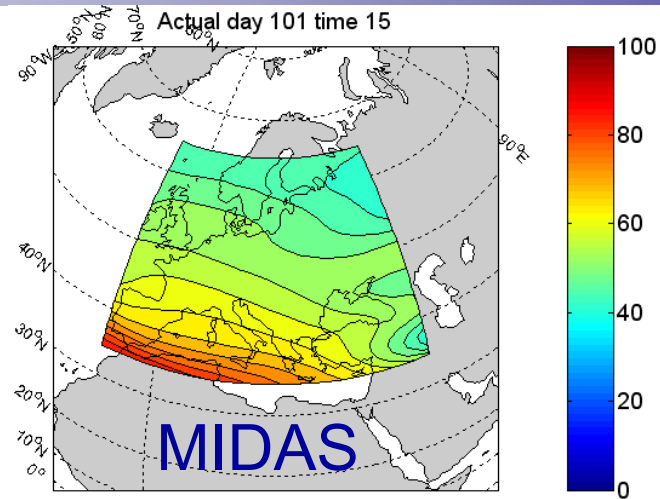
►Continuous: e.g., on-demand inversions

Output data products

Inversion at 20
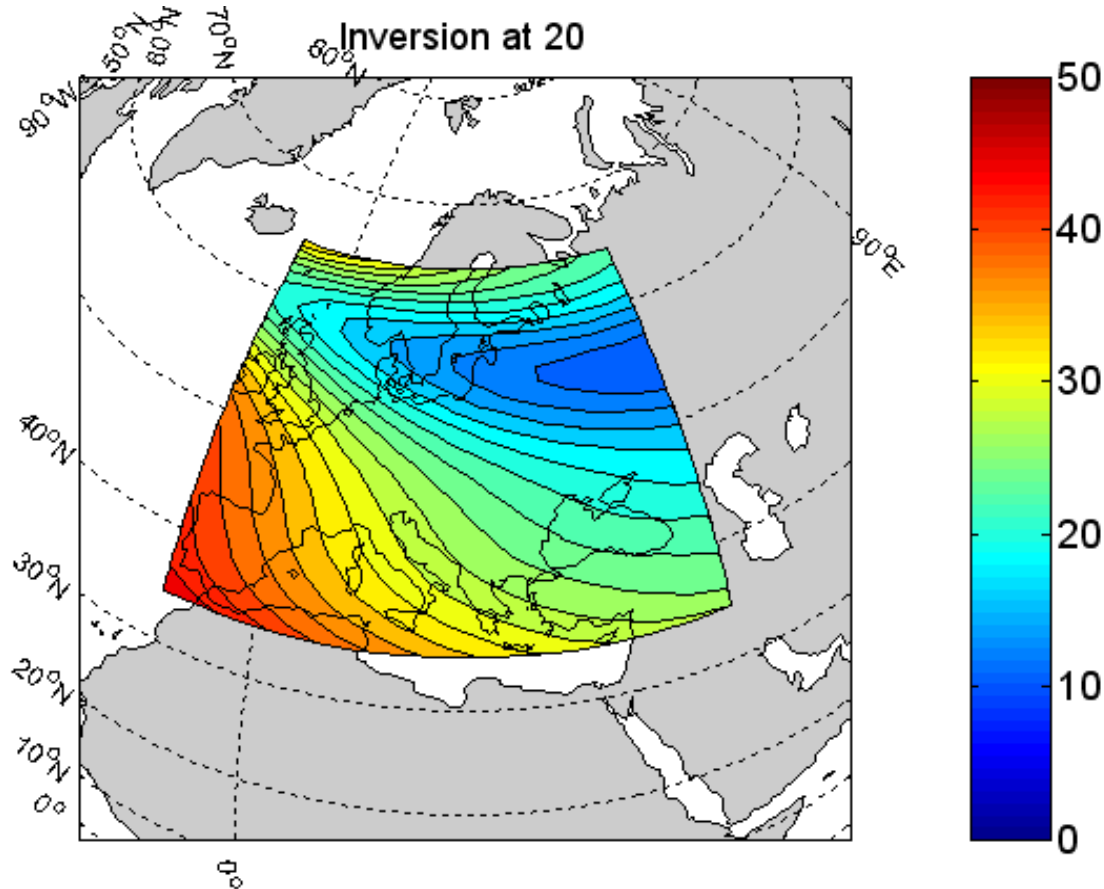
► High-level users: web-based client/server architecture

► Can be run "on demand" to produce output to produce latest image

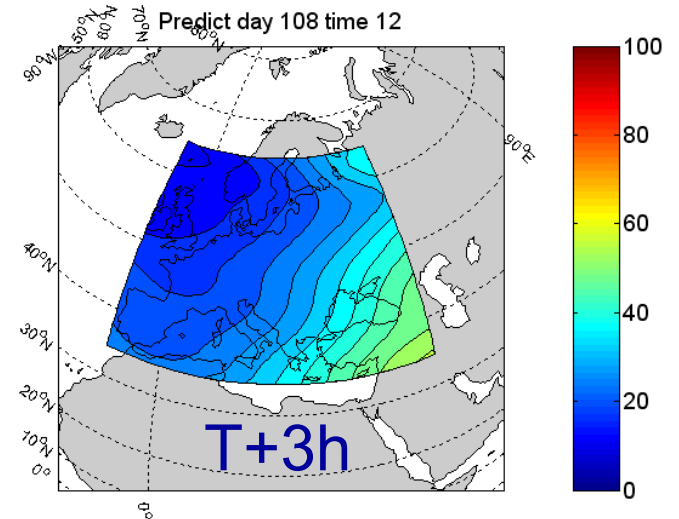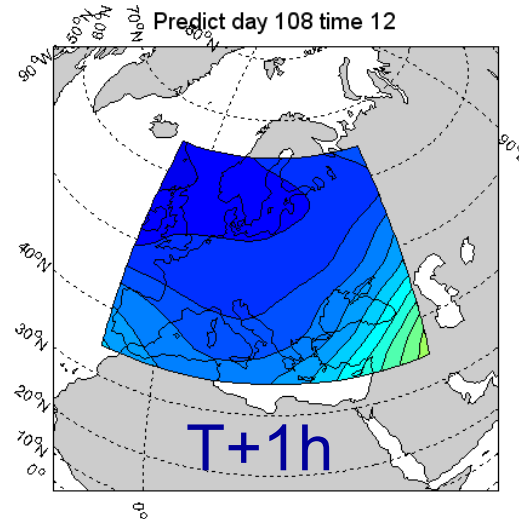► Low-level users: transmission of derived products e.g., navigation corrections

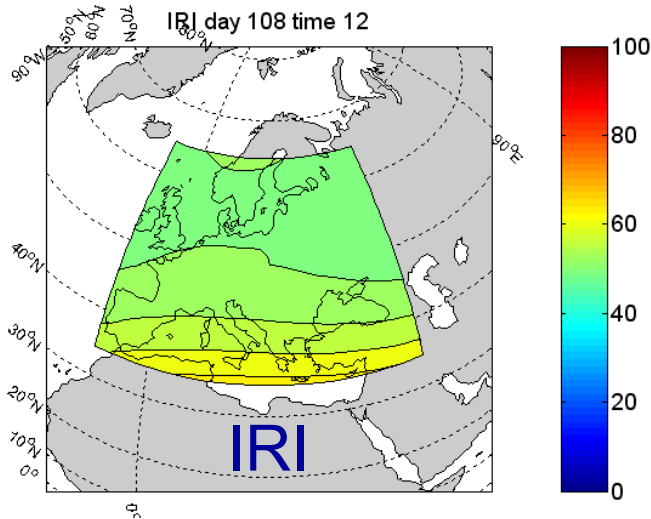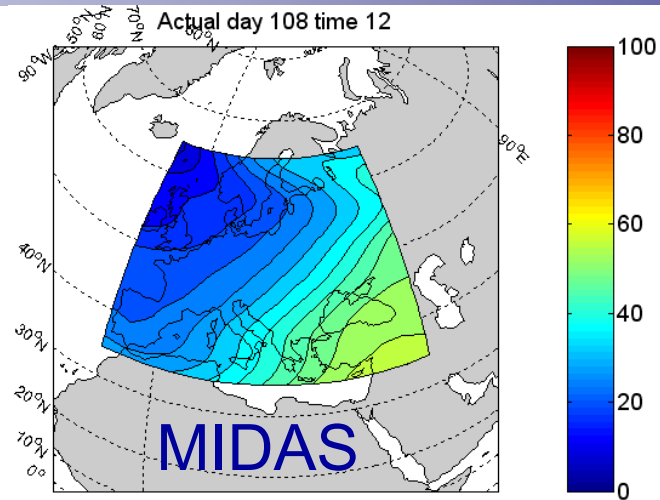Dept. of Electronic and Electrical Engineering

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Forecast performance

daytime: quiet day, storm recovery

night time: trough

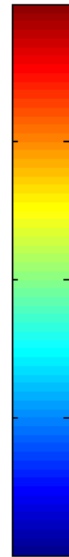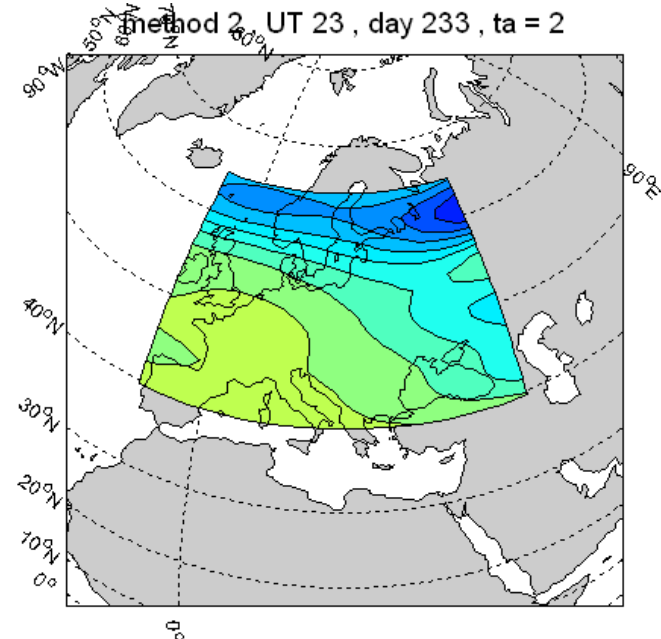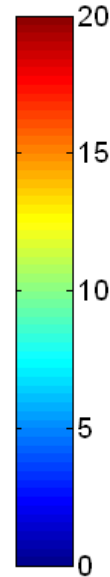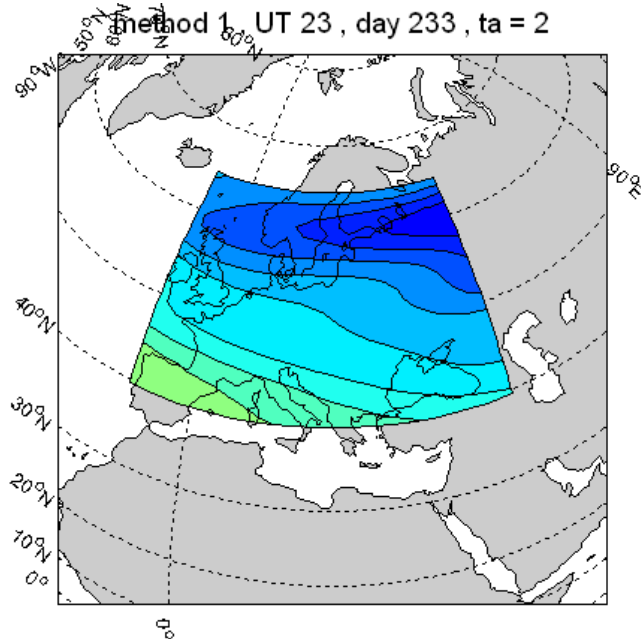Dept. of Electronic and Electrical Engineering

Day-time – quiet day

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Day-time – storm recovery
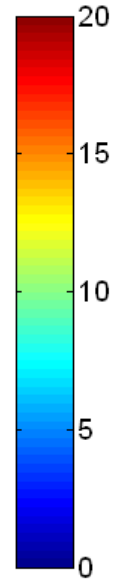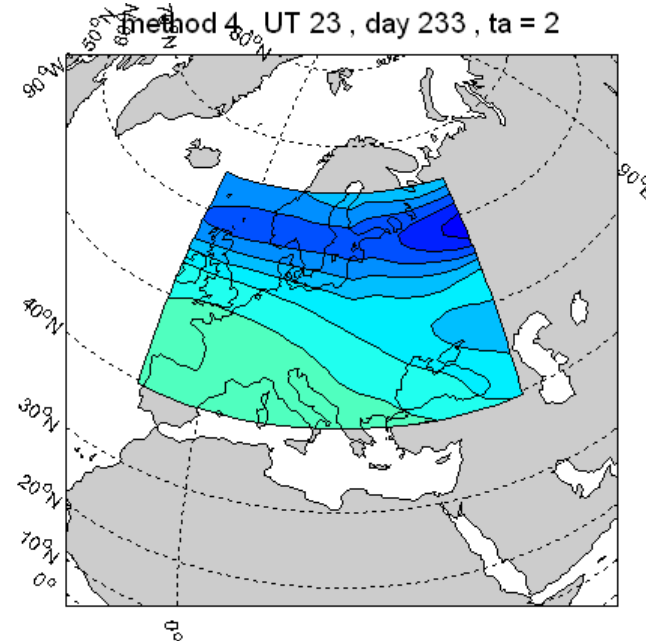
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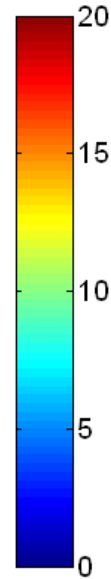# Night-time - Trough

Night-time forecasting is more tricky …

► Trough movement – not just large scale changes

► Spatial-temporal evolution of structures

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Night-time - Trough
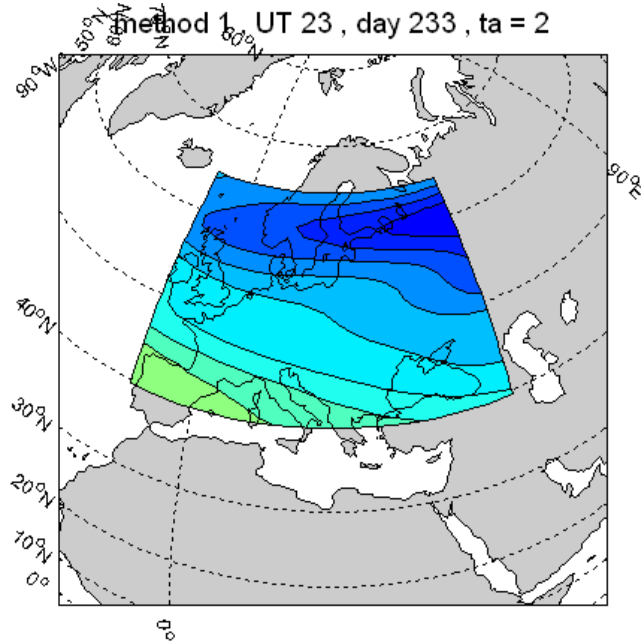
Parameterised statistical model including …

► Local time

► Trough velocity

► Magnetic activity

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Problems and solutions

delays and computation

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The unavoidable delays

► **Data acquisition – GPS receiver to OS server**

  ► Presently, the receivers run with a 30s epoch, fresh data available every hour

► **Data download time – OS server to Bath**

  ► Network dependent

► **Orbit download time – JPL to Bath**

  ► "Ultra-Rapid" orbits, twice a day, 24h orbit prediction

► **MIDAS Image reconstruction**

  ► Computational core uses sequential computation
  ► Some functions can be made parallel

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Computation issues

►Reconstruction computation time

  ►Data window needs to be long enough so as to ensure stability

  ►Image update rate – ionospheric temporal autocorrelation

For the UK, computation time is short …

►For global ionosphere - computation time for reconstruction will be significant compared to the forecast window

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Accelerating computation

►**Cluster computing …**

►MIDAS core is a linear algebra solver – can be made parallel e.g., inversion of large sparse matrices, sorting

►Ionospheric ray-tracing is a so-called "embarrassingly" parallel problem – no interdependence between rays

►**Hardware acceleration …**

►Convert MIDAS inversion core into VHDL (collaborative effort with University of Southampton)

►Field Programmable Gate Array implementation

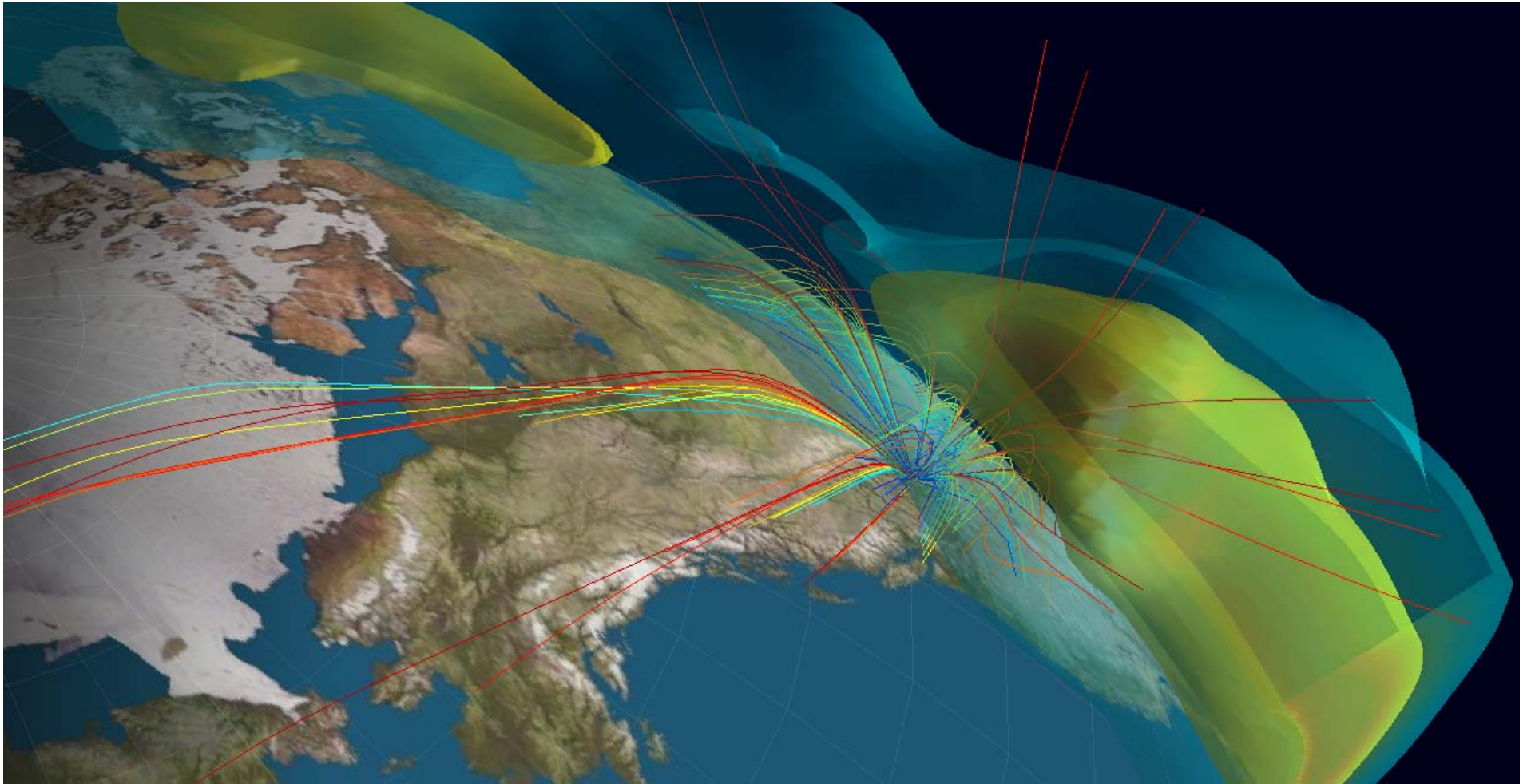►Can be used to accelerate data compression and decompression

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Applications of real-time data

who might want such data?

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Users and applications

► Characterization of HF/VHF/UHF radar coverage e.g., ray-tracing

► Military HF communications: channel assignment, secure communications, availability

► Navigation corrections: Galileo – narrowband transmission channel, GPS - transmission over cellular network

► Diagnostic tool for geodetic surveyors – Ordnance Survey: "what was the state of the ionosphere?"

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Ray-tracing through the ionosphere

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Summary

► We must live with latency, it will always be there

► Forecasting can be used to "cheat" time

  ► Forecast accuracy needs further quantification

► Computation can be accelerated

  ► Many operations are parallelizable, matrix inversion, sorting etc.

► A practical real-time system looks feasible

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The End

Acknowledgements